

Improved Interference in Wireless Sensor Networks

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Abstract. Given a set \mathcal{V} of n sensor node distributed on a 2-dimensional plane and a source node $s \in \mathcal{V}$, the *interference problem* deals with assigning transmission range to each $v \in \mathcal{V}$ such that the members in \mathcal{V} maintain connectivity predicate \mathcal{P} , and the maximum/total interference is minimum. We propose algorithm for both *minimizing maximum interference* and *minimizing total interference* of the networks. For minimizing maximum interference we present optimum solution with running time $O((\mathcal{P}_n + n^2) \log n)$ for connectivity predicate \mathcal{P} like strong connectivity, broadcast (s is the source), k -edge(vertex) connectivity, spanner, where $O(\mathcal{P}_n)$ is the time complexity for checking the connectivity predicate \mathcal{P} . The running time of the previous best known solution was $O(\mathcal{P}_n \times n^2)$ [3].

For the minimizing total interference we propose optimum algorithm for the connectivity predicate broadcast. The running time of the propose algorithm is $O(n)$. For the same problem, the previous best known result was $2(1 + \ln(n - 1))$ -factor approximation algorithm [3]. We also propose a heuristic for minimizing total interference in the case of strongly connected predicate and compare our result with the best result available in the literature. Experimental results demonstrate that our heuristic outperform existing result.

Keywords: Wireless sensor networks, Interference.

1 Introduction

A sensor node is a small size, low-power devices with limited computation and communication capabilities. A wireless sensor network (WSN) is a set of sensor nodes and each sensor of the network can measure certain physical phenomena like temperature, pressure, intensity of light or vibrations around it. Wireless networks of such sensor nodes have many potential applications, such as surveillance, environment monitoring and biological detection [1, 7]. The objective of such network is to process some high-level sensing tasks and send the data to the application [5].

Since the sensor nodes are battery operated, so minimizing energy consumption is a critical issue for designing topology of wireless sensor networks to increase its lifetime. A message packet transmitted by a sensor device to another is

often received by many nodes in the vicinity of the receiver node. This causes collision of signals and increased interference in its neighboring nodes, which leads to message packet loss. Due to packet loss the sender node needs to retransmit the message packets. Therefore, large interference of networks may result delays for delivering data packets. This would further enhance the energy consumption of nodes in network. Thus interference reduction of nodes is a crucial issue for minimizing (i) delays for delivering data packets and (ii) energy consumption of a wireless sensor network.

2 Network Model and Interference Related Problems

Definition 1. $\delta(u, v)$ denotes the Euclidean distance between two sensor nodes u and v . A range assignment is $\rho: \mathcal{V} \rightarrow \mathbb{R}$. A communication graph $G_\rho = (\mathcal{V}, E_\rho)$ is a directed graph, where \mathcal{V} is the set of sensor nodes and $E_\rho = \{(u, v) | \rho(u) \geq \delta(u, v)\}$. G_ρ is said to be strongly connected if there is a directed path between each pair of vertices $u, v \in \mathcal{V}$ in G_ρ . G_ρ is said to be an arborescence rooted at $v \in \mathcal{V}$ if there is a directed path from v to all other vertices $u \in \mathcal{V}$ in G_ρ .

Different models have been proposed to minimize the interference in sensor networks [4, 11, 10]. In this paper, we focus on the following two widely accepted models:

- **Sender Interference Model (SIM):** The interference of a node $u \in \mathcal{V}$ is the cardinality of the set of nodes to whom it can send messages directly. The set of nodes creating interference with u with respect to the range assignment ρ is denoted by $I_S^u(\rho)$ and defined by $I_S^u(\rho) = \{v \in \mathcal{V} \setminus \{u\} | \delta(u, v) \leq \rho(u)\}$, where $\rho(u)$ is the range of the node u . Therefore the interference value of node u is equal to $|I_S^u(\rho)|$ with respect to range assignment ρ .
- **Receiver Interference Model (RIM):** The interference of a node $u \in \mathcal{V}$ is the cardinality of the set of nodes from which it can receive messages directly. The set of nodes creating interference with u with respect to the range assignment ρ is denoted by $I_R^u(\rho)$ and defined by $I_R^u(\rho) = \{v \in \mathcal{V} \setminus \{u\} | \delta(u, v) \leq \rho(v)\}$, where $\rho(v)$ is the range of the node v . Therefore the interference value of node u is equal to $|I_R^u(\rho)|$ with respect to range assignment ρ .

In the interference minimization problems, the objective is to minimize the following objective functions:

- **MinMax SI (MMSI):** Given a set \mathcal{V} of n sensors, find a range assignment function ρ such that the communication graph G_ρ satisfy the connectivity predicate \mathcal{P} and maximum sender interference of the sensors in the network is minimum i.e.,

$$\min_{\rho | G_\rho \text{ satisfy } \mathcal{P}} \max_{v \in \mathcal{V}} I_S^v(\rho)$$

- **Min Total SI (MTSI):** Given a set \mathcal{V} of n sensors, find a range assignment function ρ such that the communication graph G_ρ satisfy the connectivity

predicate \mathcal{P} and total sender interference of the entire sensor network is minimum i.e.,

$$\min_{\rho | G_\rho \text{ satisfy } \mathcal{P}} \sum_{v \in \mathcal{V}} I_S^v(\rho)$$

- **MinMax RI (MMRI):** Given a set \mathcal{V} of n sensors, find a range assignment function ρ such that the communication graph G_ρ satisfy the connectivity predicate \mathcal{P} and maximum receiver interference of the sensors in the network is minimum i.e.,

$$\min_{\rho | G_\rho \text{ satisfy } \mathcal{P}} \max_{v \in \mathcal{V}} I_R^v(\rho)$$

- **Min Total RI (MTRI):** Given a set \mathcal{V} of n sensors, find a range assignment function ρ such that the communication graph G_ρ satisfy the connectivity predicate \mathcal{P} and total receiver interference of the entire sensor network is minimum i.e.,

$$\min_{\rho | G_\rho \text{ satisfy } \mathcal{P}} \sum_{v \in \mathcal{V}} I_R^v(\rho)$$

In the communication graph corresponding to a range assignment ρ , the number of out-directed edges and in-directed edges are same, which leads to the following result:

Theorem 1. *For any range assignment ρ , $\text{MTSI} = \text{MTRI}$.*

2.1 Our Contribution

In this paper, we propose algorithm for *minimizing maximum interference* and *minimizing total interference* of a given wireless sensor network. For minimizing maximum interference we present optimum solution with running time $O((\mathcal{P}_n + n^2) \log n)$ for connectivity predicate \mathcal{P} like strong connectivity, broadcast, k -edge(vertex) connectivity, spanner. Here $O(\mathcal{P}_n)$ is the time complexity for checking the connectivity predicate \mathcal{P} . The running time of the previous best known solution was $O(\mathcal{P}_n \times n^2)$ [3].

For the minimizing total interference we propose optimum algorithm for the connectivity predicate broadcast. The running time of the propose algorithm is $O(n)$. For the same problem, the previous best known result was $2(1 + \ln(n-1))$ -factor approximation algorithm [3]. We also propose a heuristic for minimizing total interference in the case of strongly connected predicate and compare our result with the best result available in the literature. Experimental results demonstrate that our heuristic outperform existing result.

We organize remaining part of this paper as follows: In Section 3, we discuss existing results in the literature. The algorithm for the optimum solution of minimizing maximum interference for different connectivity predicate appears in Section 4. In Section 5, we present optimum algorithm to minimize total interference for the connectivity predicate broadcast. A heuristic for minimizing total interference for the strongly connected predicate appears in Section 6. Finally, we conclude the paper in Section 7.

3 Related Works

Tan et al. [12] studied minimization of the average interference and the maximum interference for the highway model, where all the nodes are arbitrarily distributed on a line. For the minimum average interference problem they proposed an exact algorithm, which runs in $O(n^3 \Delta^3)$ time, where n is the number of nodes and Δ is the maximum node degree in the communication graph for the equal range assigned to each nodes equal to the maximum consecutive distance between two nodes. For the minimization of maximum interference problem, they proposed $O(n^3 \Delta^{O(k)})$ time algorithm, where $k = O(\sqrt{\Delta})$. Lou et al. [6] improves the time complexity to $O(n \Delta^2)$ for the minimization of average interference problem. Rickenbach et al. [10] proved that minimum value of maximum interference is bounded by $O(\sqrt{\Delta})$ and presented an $O(\sqrt[4]{\Delta})$ -factor approximation algorithm, where Δ is the maximum node degree in the communication graph for some equal range ρ_{\max} assigned to all the nodes.

For 2D networks, Buchin [2] considered receiver interference model and proved that minimizing the maximum interference is NP-hard whereas Bilò and Proietti [3] considered sender interference model and proposed a polynomial time algorithm for minimizing the maximum interference. Their algorithm works for many connectivity predicate like simple connectivity, strong connectivity, broadcast, k -edge(vertex) connectivity, spanner, and so on. They also proved that any polynomial time α -approximation algorithm for minimum total range assignment problem with connectivity predicate \mathcal{P} can be used for designing a polynomial time α -approximation algorithm for minimum total interference problem for \mathcal{P} . Panda and Shetty [9] considered 2D networks with sender centric model and proposed an optimal solution for minimizing the maximum interference and a 2-factor approximation algorithm for average interference. Moscibroda and Wattenhofer [8] proposed $O(\log n)$ -factor greedy algorithm for minimizing average interference.

4 Minimization of Maximum Interference

In this section we consider sender centric interference model. Given a set $\mathcal{V} = \{v_1, v_2, \dots, v_n\}$ of n nodes distributed on a 2D plane, the objective is to find a range assignment $\rho : \mathcal{V} \rightarrow \mathbb{R}$ such that the corresponding communication graph G_ρ contains connectivity predicate \mathcal{P} like strong connectivity, broadcast, k -edge(vertex) connectivity, spanner etc. Bilò and Proietti considered the same problem and proposed $O(\mathcal{P}_n \times n^2)$ time algorithm for optimum solution, where \mathcal{P}_n is the time required to check predicate \mathcal{P} for a given communication graph [3].

Here we propose an algorithm to solve the above problem optimally. The running time of our algorithm is $O((\mathcal{P}_n + n^2) \log n)$, which leads to a big improvement over [3].

4.1 Algorithm

In the network, the number of nodes is n , which means maximum possible interference of a node is $n - 1$. The main idea of our algorithm is very simple: first we start range assignment to each of the node in such a way that the interference of each node is k ($1 \leq k \leq n - 1$). Next we test whether the communication graph contains the connectivity predicate \mathcal{P} or not. If the answer is *yes*, then we try for lower values of k . Otherwise we try for higher values of k . The pseudo code for the minimizing maximum sender interference (MMSI) algorithm described in Algorithm 1.

In the algorithm we use a matrix M of size $n \times n - 1$ and $M(i, j) = \delta(v_i, u)$, where $u \in \mathcal{V}$ such that if $\rho(v_i) = \delta(v_i, u)$, then $I_S^{v_i}(\rho) = j$ for all $i = 1, 2, \dots, n$ and $j = 1, 2, \dots, n - 1$. Elements of the i -th row are $\delta(v_i, v_1), \delta(v_i, v_2), \dots, \delta(v_i, v_{i-1}), \delta(v_i, v_{i+1}), \dots, \delta(v_i, v_n)$ in ascending order from left to right.

Algorithm 1 Optimum algorithm for minimizing maximum sender interference

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1: Input: a set  $\mathcal{V} = \{v_1, v_2, \dots, v_n\}$  of  $n$  nodes and a connectivity predicate  $\mathcal{P}$ .
2: Output: a range assignment  $\rho$  such that communication graph  $G_\rho$  contains connectivity predicate  $\mathcal{P}$  and an interference value (MMSI).
3: Construct the matrix  $M$  as described above.
4:  $\ell \leftarrow 0, r \leftarrow n - 1$ 
5: while ( $\ell \neq r - 1$ ) do
6:   for ( $i = 1, 2, \dots, n$ ) do
7:      $\rho(v_i) = M(i, \frac{\ell+r}{2})$ 
8:   end for
9:   Construct the communication graph  $G_\rho$  corresponding to  $\rho$ .
10:  Test whether  $G_\rho$  contains connectivity predicate  $\mathcal{P}$  or not.
11:  if (answer of the above test is yes) then
12:     $r = \lfloor \frac{\ell+r}{2} \rfloor$  /* maximum interference is at most  $\lfloor \frac{\ell+r}{2} \rfloor$  */
13:  else
14:     $\ell = \lfloor \frac{\ell+r}{2} \rfloor$  /* minimum interference is greater than  $\lfloor \frac{\ell+r}{2} \rfloor$  */
15:  end if
16: end while
17: for ( $i = 1, 2, \dots, n$ ) do
18:    $\rho(v_i) = M(i, r)$ 
19: end for
20: Return( $\rho, r$ )

```

Theorem 2. *Algorithm 1 computes minimum of maximum sender interference (MMSI) optimally and its worst case running time is $O((\mathcal{P}_n + n^2) \log n)$.*

Proof. Let ρ (resp. ρ') be the range assignment to the nodes in \mathcal{V} when the sender interference of each node is ℓ (resp. r). The correctness of the Algorithm 1 follows from the fact (i) the Algorithm 1 stops when $\ell = r - 1$ such that G_ρ does not contain connectivity predicate \mathcal{P} , whereas $G_{\rho'}$ contains connectivity predicate \mathcal{P} and (ii) if $\rho(u) > \rho'(u)$, then $I_S^u(\rho) \geq I_S^u(\rho')$.

The construction time of matrix M (line number 3 of the Algorithm 1) takes $O(n^2 \log n)$ time in worst case. Construction of the communication graph G_ρ (line number 9 of the Algorithm 1) and testing connectivity predicate (line number 10 of the Algorithm 1) take $O(\mathcal{P}_n)$ time. Again, each execution of **while** loop in line number 5 reduce the value $(\ell - r)$ by half of its previous value. Therefore, Algorithm 1 call this **while** loop $O(\log n)$ time. Thus, the time complexity results of the theorem follows.

5 Minimization of Total Interference

Given a set $\mathcal{V} = \{v_1, v_2, \dots, v_n\}$ of n nodes and a source node $s \in \mathcal{V}$ distributed on a 2D plane, the objective is to find a range assignment $\rho : \mathcal{V} \rightarrow \mathbb{R}$ such that the corresponding communication graph G_ρ contains an arborescence rooted at s (connectivity predicate is broadcast) and the total interference (sender/receiver) is minimum. Bilò and Proietti considered the same problem and proposed $2(1 + \ln(n - 1))$ -factor approximation algorithm [3]. Here we propose a very simple optimum algorithm. The running time of the algorithm is linear. The pseudo code for the minimum total sender interference (MTSI) algorithm described in Algorithm 2. Though the propose algorithm is trivial, we are proposing it for completeness of the literature.

Lemma 1. *For any range assignment ρ such that the communication graph $G_\rho = (\mathcal{V}, E_\rho)$ contains arborescence rooted at any node u in the network of n nodes, the minimum total sender interference of the networks is at least $n - 1$.*

Proof. Since the communication graph G_ρ contains an arborescence rooted at u , each node $v \in \mathcal{V} \setminus \{u\}$ has an incoming edge. Therefore, the total receiver interference is at least $n - 1$. Thus, the lemma follows from Theorem 1.

Algorithm 2 Optimum algorithm for minimizing maximum sender interference

- 1: **Input:** a set $\mathcal{V} = \{v_1, v_2, \dots, v_n\}$ of n nodes and a source node $s \in \mathcal{V}$.
 - 2: **Output:** a range assignment ρ such that communication graph G_ρ contains an arborescence rooted at s and total interference (MTSI).
 - 3: **for** $(i = 1, 2, \dots, n)$ **do**
 - 4: $\rho(v_i) = 0$
 - 5: **end for**
 - 6: Find the farthest node $u \in \mathcal{V}$ from s .
 - 7: $\rho(s) = \delta(s, u)$
 - 8: **Return** $(\rho, n - 1) /* \sum_{v \in \mathcal{V}} I_S^v(\rho) = n - 1 */$
-

Theorem 3. *Algorithm 2 produces optimum total interference in $O(n)$ time.*

Proof. The correctness of the algorithm follows from (i) the fact that total interference produce by Algorithm 2 is $n - 1$ and (ii) Lemma 1. Time complexity follows from the **for** loop (line number 3) and line number 6.

6 Heuristic for Strongly Connected Predicate

In this section, we propose a heuristic to minimize total interference for strongly connected predicate i.e given a set $\mathcal{V} = \{v_1, v_2, \dots, v_n\}$ of n nodes distributed on a 2D plane, we design a heuristic for range assignment ρ such that the communication graph G_ρ is strongly connected. Experimental results presented in the Subsection 6.1 demonstrate that our heuristic perform very well compare to existing result in the literature.

Algorithm 3 Heuristic to minimizing total sender interference for Strongly Connected Predicate

- 1: **Input:** a set $\mathcal{V} = \{v_1, v_2, \dots, v_n\}$ of n nodes.
 - 2: **Output:** a range assignment ρ such that communication graph G_ρ is strongly connected and total interference of the network.
 - 3: **for** $(i = 1, 2, \dots, n)$ **do**
 - 4: $\rho(v_i) \leftarrow 0$ /* initial range assignment */
 - 5: $|I_S^{v_i}(\rho(v_i))| \leftarrow 0$ /* initial interference assignment */
 - 6: $T_I \leftarrow 0$ /* initial total interference */
 - 7: **end for**
 - 8: $\mathcal{U}_1 = \{v_1\}$ and $\mathcal{U}_2 = \mathcal{V} \setminus \{v_1\}$
 - 9: **while** $(\mathcal{U}_2 \neq \emptyset)$ **do**
 - 10: Choose $u_1, u'_1 \in \mathcal{U}_1$ and $u_2 \in \mathcal{U}_2$ such that $|I_S^{u_1}(\delta(u_1, u_2))| - |I_S^{u_1}(\rho(u_1))| + |I_S^{u_2}(\delta(u_2, u'_1))| \leq |I_S^{w_1}(\delta(w_1, w_2))| - |I_S^{w_1}(\rho(w_1))| + |I_S^{w_2}(\delta(w_2, w'_1))|$ for all $w_1, w'_1 \in \mathcal{U}_1$ and $w_2 \in \mathcal{U}_2$.
 - 11: $T_I = T_I + |I_S^{u_1}(\delta(u_1, u_2))| - |I_S^{u_1}(\rho(u_1))| + |I_S^{u_2}(\delta(u_2, u'_1))|$ /* total interference update */
 - 12: $\rho(u_1) = \delta(u_1, u_2)$ and $\rho(u_2) = \delta(u_2, u'_1)$ /* new range assignments */
 - 13: $|I_S^{u_1}(\rho(u_1))| = |I_S^{u_1}(\delta(u_1, u_2))|$ and $|I_S^{u_2}(\rho(u_2))| = |I_S^{u_1}(\delta(u_2, u'_1))|$ /* new interference assignments */
 - 14: $\mathcal{U}_1 = \mathcal{U}_1 \cup \{u_2\}$ and $\mathcal{U}_2 = \mathcal{U}_2 \setminus \{u_2\}$
 - 15: **end while**
 - 16: Return(ρ, T_I)
-

Theorem 4. *The running time of the Algorithm 3 is polynomial in input size.*

Proof. The input size of the Algorithm 3 is n . In each execution of **While** loop (line number 9 of the Algorithm 3), the size of the set \mathcal{U}_2 is decreasing by 1. Choosing the vertices u_1, u'_1, u_2 (line number 10 of the Algorithm 3) needs $O(n^3)$ time. Thus, the time complexity result of the theorem follows.

6.1 Experimental Results

The model consists of n sensor nodes randomly distributed in a 1000×1000 square grid. For different values of n , we execute our heuristic 100 times for different input instances. We have taken average value of the total interference

of the nodes in the network. In Figure 1, we have shown average interference of our heuristic and compare it with the algorithm improved SMIT [9]. In Table 6.1, we have shown the comparison of the total interference between our heuristic and the algorithm proposed in [9]. These experimental results demonstrate that our heuristic outperform existing algorithm.

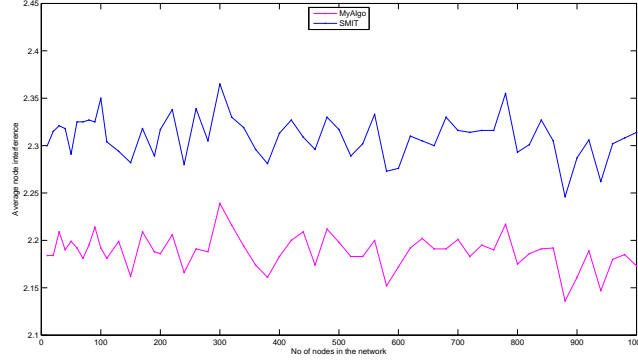


Fig. 1. Average node interference

# of nodes (n)	Total Average Interference	
	Our Heuristic	Improved SMIT [9]
10	2.184	2.30
20	2.184	2.315
30	2.209	2.321
50	2.199	2.291
70	2.181	2.325
100	2.192	2.350
200	2.186	2.317
300	2.239	2.365
400	2.183	2.313
500	2.198	2.317
700	2.201	2.316
900	2.161	2.287
1000	2.173	2.314

Table 1. Simulation results for total interference

7 Conclusion

In this paper we considered 2D networks i.e., the wireless nodes are distributed on a 2D plane. All the results presented in this paper are applicable in 3D networks

also. Here we considered interference (sender interference model) minimization problem in wireless networks. We proposed algorithm for *minimizing maximum interference* and *minimizing total interference* of a given networks. For minimizing maximum interference we presented optimum solution with running time $O((\mathcal{P}_n + n^2) \log n)$ for connectivity predicate \mathcal{P} like strong connectivity, broadcast, k -edge(vertex) connectivity, spanner, where n is the number of nodes in the network and $O(\mathcal{P}_n)$ is the time complexity for checking the connectivity predicate \mathcal{P} . The running time of the previous best known solution was $O(\mathcal{P}_n \times n^2)$ [3]. Therefore, our solution is a significant improvement over the best known solution with respect to time complexity.

For the minimizing total interference we proposed optimum algorithm for connectivity predicate broadcast. The running time of the proposed algorithm is $O(n)$. For the same problem, the previous best known result was $2(1 + \ln(n - 1))$ -factor approximation algorithm [3]. Therefore, our solution is a significant improvement over the existing solution in the literature. We also proposed a heuristic for minimizing total interference in the case of strongly connected predicate and compare our result with the best result available in the literature. Experimental results demonstrate that our heuristic outperform existing result.

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